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Salinity Calculations in the Coastal Modeling System

by Honghai Li, Christopher W. Reed, and Mitchell E. Brown

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes procedures to calculate salinity change within the Coastal Modeling System (CMS) operated in the Surface-water Modeling System (SMS), version 11.0. The CMS is a two-dimensional (2-D) hydrodynamic and sediment transport model designed for coastal and inlet applications, and the SMS is a graphical user interface utility for PCs as developed by the U.S. Army Corps of Engineers (USACE). For calculating salinity with the 2-D CMS, the project area must be well-mixed in the vertical dimension. The procedure and the CMS verification are illustrated by the salinity modeling in Matagorda Bay, Texas.

INTRODUCTION: Salinity refers to the salt content of water. Its value typically runs from 0 for fresh water to 31-35 ppt (parts per thousand) for ocean water. In water bodies with poor mixing and limited water exchange, or experiencing high evaporation, salinity can be higher and lead to formation of brine. Table 1 presents typical values and nomenclature for describing degree of saline water:

Table 1. Water salinity.

Fresh water	Brackish water	Saline water	Brine
< 0.05 %	0.05 – 3 %	3 – 5 %	> 5 %
< 0.5 ppt	0.5 – 30 ppt	30 – 50 ppt	> 50 ppt

In coastal zones and estuaries, both temporal and spatial variations in salinity are controlled by changes in circulation, waves, tides, precipitation, evaporation, and freshwater inflows. These changes in salinity can have major effects on water density and water stratification, which can modify circulation patterns. Dynamic behavior of suspended sediment can be controlled by the salinity-driven flow and mixing. Any sustained changes to salinity can change directly the aggregation and consolidation of cohesive sediment as well (Nicholson and O'Connor 1986). Salinity can also alter the water chemistry that impacts marine organisms, the distribution and abundance of which will change water turbidity in coastal and estuarine systems. Modifications of coastal inlets, such as channel deepening and widening and rehabilitation or extension of jetties, may alter the salinity distribution within the estuary.

COASTAL MODELING SYSTEM: The CMS calculates water levels, currents and waves through the coupling between a hydrodynamic model, CMS-Flow and a wave spectral model, CMS-Wave. These two models can also interact dynamically to simulate sediment and salinity transport, and morphology change (Buttolph et al. 2006; Lin et al. 2008).

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CMS-Flow is a 2-D finite-volume model that solves the mass conservation and shallow-water momentum equations of water motion. CMS-Flow is forced by water surface elevation (e.g., from tide), wind and river discharge at the model boundaries, and wave radiation stress and wind field over the model computational domain. Physical processes pertinent to the present study calculated by CMS-Flow include wave-current interaction, sediment transport, morphology change, and representation of a non-erodible bottom (reef). Additional capabilities include wetting and drying, space-varying bottom-friction, salinity transport, efficient grid storage in memory, and hot-start options.

CMS-Wave is a 2-D steady-state (time-independent) spectral wave transformation model. The model contains theoretically derived approximations of wave diffraction, reflection, and wave-current interaction for wave simulations at coastal inlets with jetties and breakwaters. It employs a forward-marching and finite-difference method to solve the wave action conservation equation. CMS-Wave can operate in half- and full-plane mode. In a coastal half-plane, primary waves can propagate only from the seaward boundary toward shore. In the full-plane mode, CMS-Wave performs the backward-marching for seaward spectral transformation after the forward-marching is completed.

SALINITY CALCULATIONS IN CMS: The CMS calculates the salinity field based on the following 2-D salinity conservation equation:

$$\frac{\partial(Sd)}{\partial t}+\frac{\partial(Sq_x)}{\partial x}+\frac{\partial(Sq_y)}{\partial y}=\frac{\partial}{\partial x}\left[K_x d\frac{\partial S}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y d\frac{\partial S}{\partial y}\right]+(P-E)S \tag{1}$$

where S is depth-averaged salinity; d is total water depth, q_x and q_y are flow per unit width in the x- and y-axis direction, respectively; K_x and K_y are diffusion coefficients of salt in the corresponding x- and y-axis direction, and P and E are precipitation and evaporation in m/year, respectively. Equation (1) represents the horizontal fluxes of salt in water bodies and is balanced by exchanges of salt via diffusive fluxes. Major processes contributing to the salinity are freshwater inflows from rivers, vertical fluxes of freshwater by precipitation and evaporation at the water surface, and groundwater fluxes, which can be specified as the surface and bottom boundary conditions in the equation.

MODEL ASSUMPTIONS: CMS-Flow is presently capable of 2-D salinity computations in both the explicit and implicit solvers. The simulation of salinity can often require a three-dimensional (3-D) solution due to the presence of vertical salinity gradients that can influence the flow significantly. It is therefore important to understand the limitations of 2-D salinity simulations, and apply them only when the assumptions inherent in 2-D simulations are valid. Typically, 2-D salinity simulations are valid when the salinity is well mixed over the water column. These conditions are usually met for shallow bays with open exchanges to the ocean or gulf, and strong tidal signals and sufficient wind energy to provide the vertical mixing. Also, the assumption of sufficient energy to mix over the water column is valid under storm conditions, even for deeper water bodies. Finally, when the exchange with the open sea is restricted by an inlet, the tidal range is an important indicator of vertical mixing conditions. For low tide ranges, significant vertical stratification can occur, even in shallow bays and estuaries, especially when the winds are calm. Pritchard (1955) and Cameron and Pritchard (1963) have classified estuaries

using stratification and salinity distribution as the governing criteria, and these classifications can be used for guidance in applying the 2-D simulations.

The lateral mixing for salinity in the CMS Flow model is the same as the lateral mixing in the momentum equations.

SALINITY MODELING IN MATAGORDA BAY, TEXAS: In this section, the salinity modeling is described to demonstrate the CMS capability in Matagorda Bay, Texas. The salinity calculations are calibrated against measurements at five monitoring stations.

Background: Matagorda Bay is the largest estuarine bay on the coast of Texas and is connected to the Gulf of Mexico and the Gulf Intracoastal Waterway (GIWW) through Matagorda Ship Channel (MSC), a federally-maintained inlet, and Pass Cavallo, a natural inlet just downdrift from the MSC (Figure 1). The bay has an average water depth of 2 m and the hydrodynamics in this shallow bay are frequently dominated by wind. The large surface area of the bay results in the relatively large tidal prism, although the mean tidal range is only 0.26 m (Kraus et al. 2006). Wind and tide provide sufficient energy to mix water vertically, indicating that depth-averaged circulation and salinity simulations are applicable to the bay as the salinity is well mixed over the water column (EHI 2006; Kraus et al. 2006).

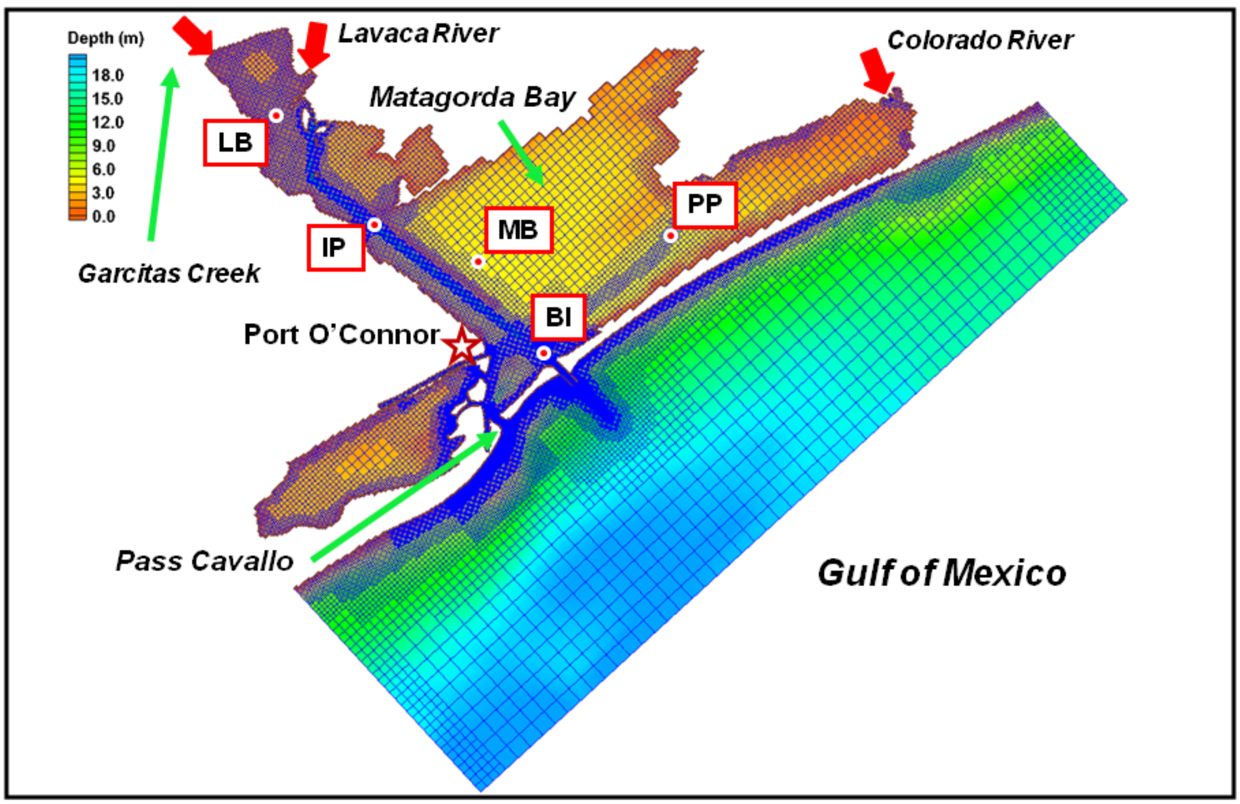


Figure 1. CMS domain, quadtree grid, and bathymetry of Matagorda Bay, TX. Red dots are the survey stations and red arrows indicate freshwater inflow locations.

Freshwater discharges into the bay come from a number of streams along the coast. The Colorado and the Lavaca Rivers provide most of the inflows. However, “the freshwater

discharge is typically less than 10 percent of the daily tidal exchange" in the bay (Kraus et al. 2006) (Figure 1). The bay entrance is protected by dual jetties from ocean waves. Momentum transfer, diffusive process and spatial distributions of salinity in the system are mostly controlled by wind, tide, and freshwater inflows.

In application of the CMS to Matagorda Bay, a quadtree grid system was developed to discretize the bay and the offshore. The computational domain extends approximately 80 km alongshore and 20 km offshore, and the seaward boundary of the domain reaches to the 25 m isobath. Figure 1 shows the quadtree grid with 70,000 ocean cells, bathymetric features of Matagorda Bay, and the adjoining nearshore area. The CMS grid permits fine resolution in areas of high interest such as jetties and channels. The implicit solver of the CMS, with a large time step of 15 minutes, was employed for the simulation. Comparing to the explicit solver for a similar model, the computation time was reduced by more than 50 percent with the implicit version of the CMS.

An extensive bay survey program was conducted by Evans-Hamilton, Inc. (EHI) in 2005 (EHI 2006). The data include currents, water levels, salinity, total suspended solids, and waves throughout the bay. Daily freshwater inflows are available at three U.S. Geological Survey (USGS) gages, the Colorado River near Bay City, TX, the Lavaca River near Edna, TX, and the Garcitas Creek near Inez, TX. Figure 1 shows the three freshwater inflow locations and five salinity survey sites as indicated by red arrows and red dots, respectively. The salinity data sites include Matagorda Bay (MB), Port of Palacios (PP), Bird Island (BI), Lavaca Bay (LB), and Indian Point (IP), and water surface elevation data were monitored at BI. Table 2 lists the instrument latitude/longitude locations and the sensor depths. Those data inside the bay are used to calibrate and validate the CMS salinity calculations from 20 November to 10 December 2005.

Table 2. Salinity instrument locations and sensor depths.

Station	Layer	Depth (m)	Latitude (N, degree)	Longitude (W, degree)
BI	Surface	1.22	28.44182	96.34500
	Mid	3.05	28.44182	96.34500
MB	Bottom	4.11	28.52142	96.40705
PP	Mid	2.13	28.53990	96.22090
IP	Surface	0.91	28.55227	96.50432
	Mid	3.05	28.55227	96.50432
	Bottom	5.79	28.55227	96.50432
LB	Mid	1.52	28.65192	96.59573

CMS-Flow is driven by time-dependent water surface elevation at the offshore open boundary, wind forcing over the surface boundary, and freshwater inflows from rivers and tributaries. Besides the above-described river flows, water surface elevation forcing is downloaded from a NOAA tidal gage at Corpus Christi, TX, and wind data is measured at Port O'Connor (Figure 1). Time varying salinity values at BI are also specified along the open boundaries with the water surface elevation and the river boundaries with the freshwater inflows (Figure 1). The initial salinity field is specified to the entire CMS domain as well.

CMS Setup for Salinity Calculation:

1. **CMS-Flow setup:** The CMS hydrodynamic input files for Matagorda Bay are required and prepared by the SMS shown in Figure 2.

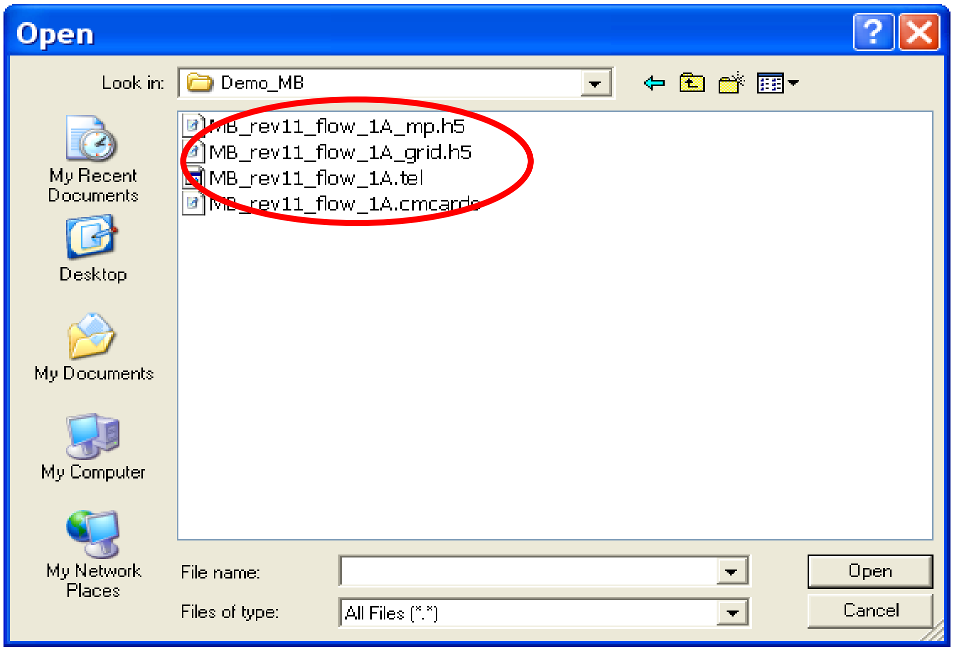


Figure 2. Files for the CMS-Flow salinity simulation.

After opening "MB_rev11_flow_1A.cmcards" in the SMS, choose *CMS-Flow* | *Model Control*, click on *Salinity*, and select *Calculate salinity* (Figure 3). A default time step equal to the hydrodynamic time step has been specified. In this case, 900 sec is used for the salinity calculation.

2. **Salinity initial condition:** Because of the large spatial variability of salinity in a coastal system, it usually requires long spin-up periods for a salinity simulation to reach to the present salinity distribution, which could range from a few days to weeks. To shorten the spin-up time, an accurate initial condition for the salinity field should be specified. There are two options to assign the initial salinity condition in CMS-Flow:

   i) **A global initial salinity:** Specify a constant initial value for the entire model domain. The salinity value can be specified by checking the *Global concentration (ppt)* under the *Initial condition* (Figure 3). If this option is applied, it is best to define an average representative salinity for the entire domain.

   ii) **Spatially varying initial salinity:** Generate a spatially varying initial salinity field by choosing the *Spatially varied* toggle under the *Initial condition* (Figure 3). Clicking the *Create Dataset* and assigning a value under the *Default concentration (ppt)* in the pop-up window will generate a new dataset with a constant initial salinity value. Clicking *OK* to close this window and then clicking *OK*, to close the *CMS-FLOW Model Control* window, will cause the dataset, *Salinity Initial Concentration*, to appear in the CMS-Flow data tree, as shown in Figure 4a. Highlight the dataset to specify different salinity values in the CMS domain in the same way to modify other datasets such as *D50* or *Hard Bottom*.

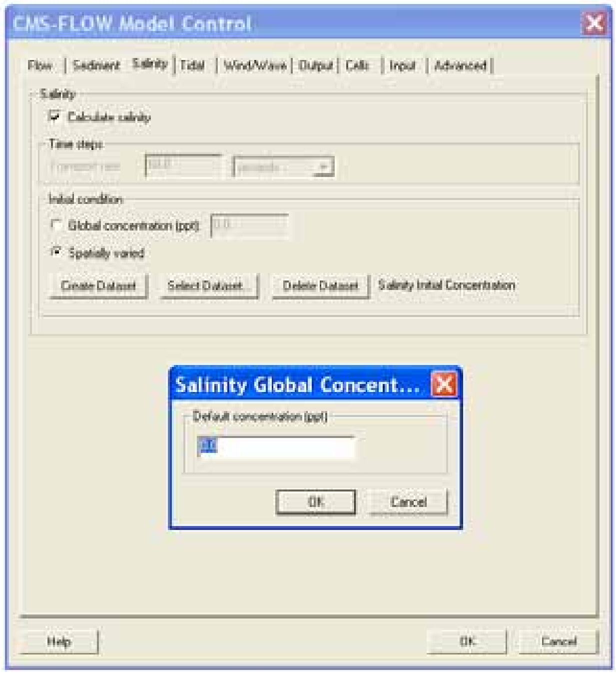
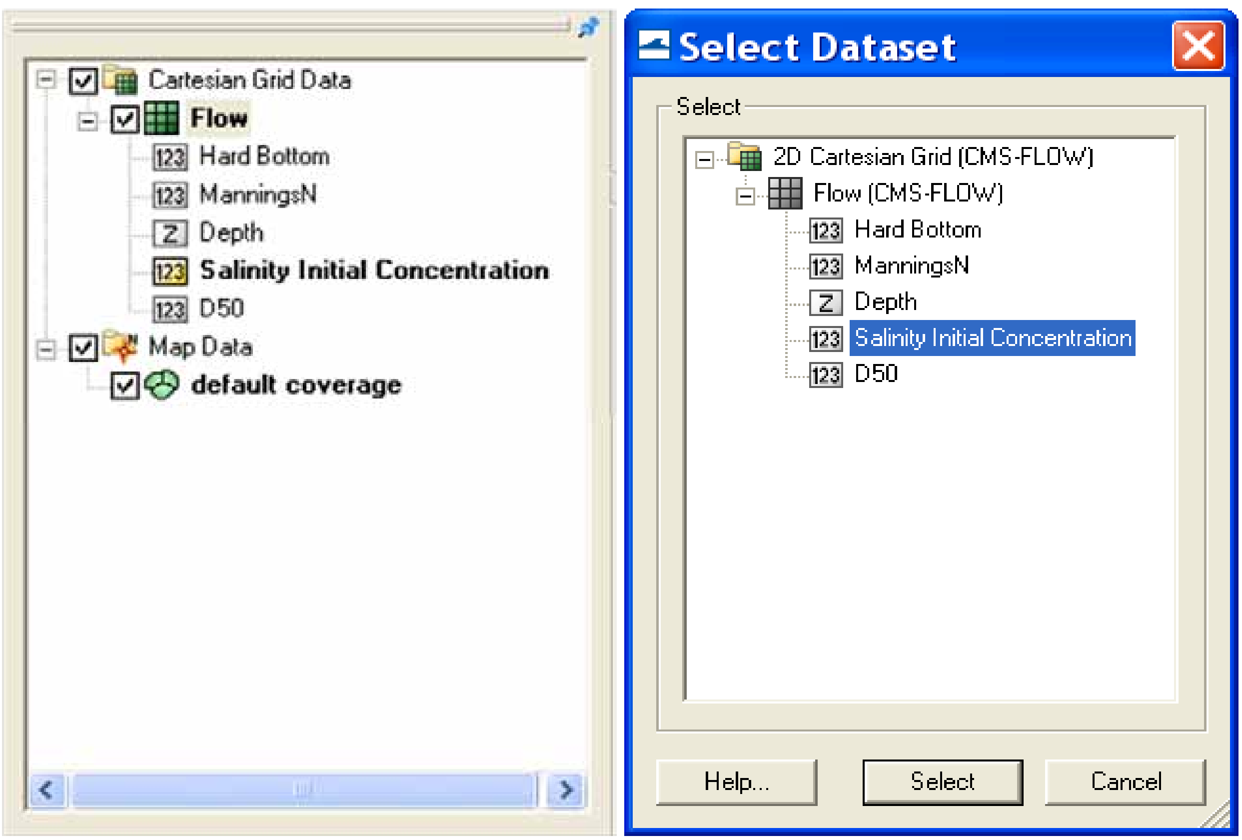


Figure 3. Setting up the salinity calculation and specifying spatially varied initial salinity.



(a) (b)

Figure 4. CMS-Flow data tree.

The dataset for a spatially varying initial salinity can also be generated by using the *Data Calculator* tool in the *Data* menu (Demirbilek et al. 2008). For an existing dataset, click the *Select Dataset* under the *Spatially varied* toggle and then select the dataset for the initial salinity that already exists (Figure 4b).

Based on the historical survey data, initial salinity is assigned in the dataset, *Salinity Initial Concentration*, for the Matagorda Bay system. The salinity varies from 21.0 ppt near the mouth of the Lavaca River to 33.0 ppt at the offshore open boundary (Figure 5).

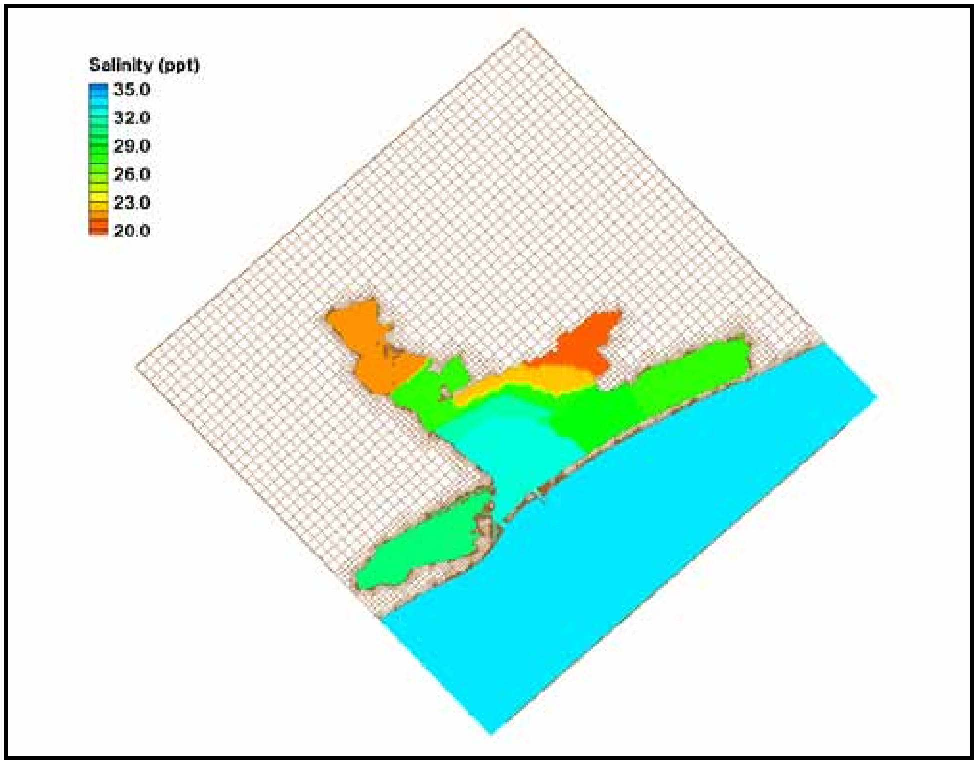


Figure 5. Initial salinity distribution.

3. **Salinity boundary conditions:** To calculate salinity transport, salinity values at CMS-Flow boundaries need to be specified. Salinity may be specified at two boundary types in the CMS: water surface elevation (WSE) boundary (*WSE-forcing* boundary) (Figure 6a) and freshwater inflow boundary (*Flow rate-forcing* boundary) (Figure 6b).

   i) **WSE-forcing boundary:** Using the *Select Cellstring* tool and clicking/ highlighting, the cellstring of water surface elevation boundary can be specified as shown in Figure 6a. Selecting *CMS-Flow | Assign BC* will open the *CMS-Flow Boundary Conditions* window (Figure 7). A time series of salinity can be assigned along the *WSE-Forcing* boundary by clicking the *Curve undefined* under *Salinity* on the left hand side of the dialog.

   The time series is specified either by clicking the *Import* button to read a salinity boundary input file in xys format (Figure 8) (Aquaveo 2010), or by entering time and salinity values manually in two separate data columns, or by importing salinity data from an opened *Excel* file by using *Copy/Paste*.

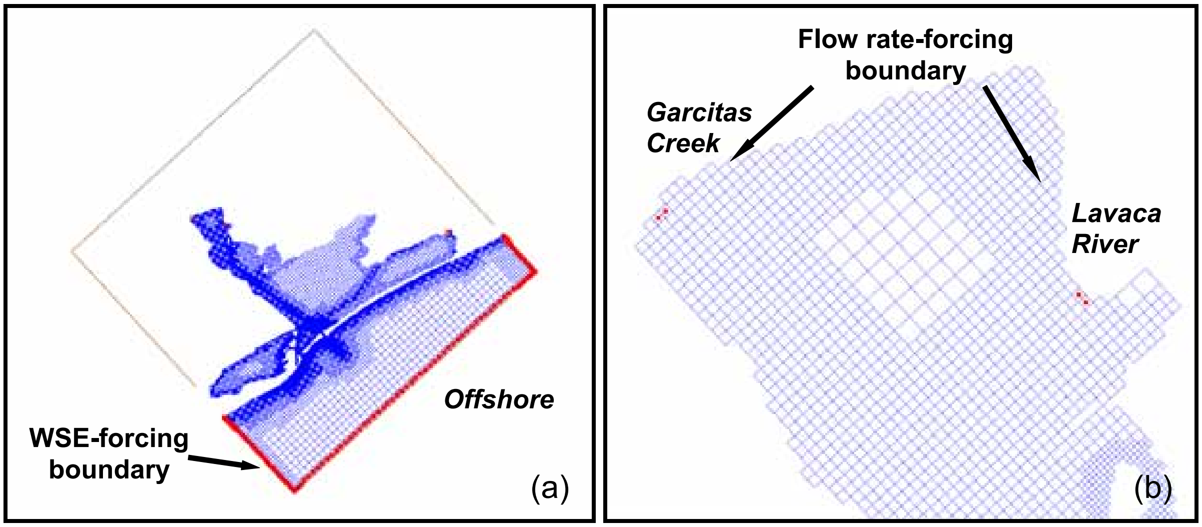


Figure 6. Salinity boundary types in the CMS.

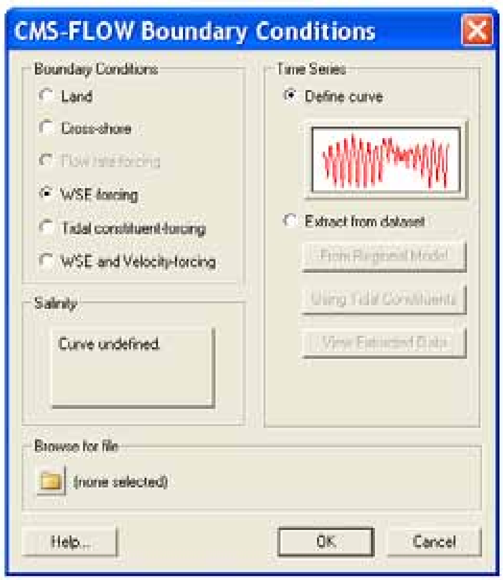


Figure 7. Salinity specifications along the *WSE-forcing* boundary.

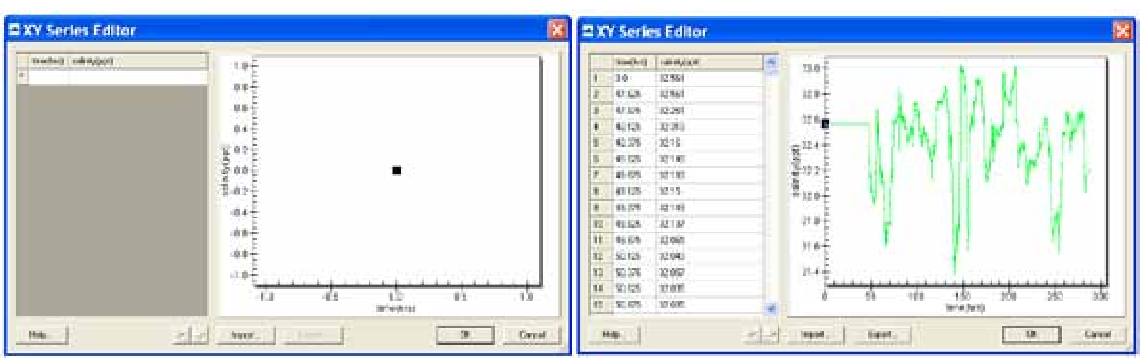


Figure 8. Salinity boundary input from a xys file.

The salinity and water surface elevation measurements at Pass Cavallo and the NOAA Corpus Christi Gage were assigned to the offshore boundary. The 12-day time series of salinity data (November-December 2005) is shown for the *WSE-forcing* boundary in Figure 8. Salinity at this location varies between 31.5 and 33.0 ppt and shows apparent influence of the ocean during the period.

ii) ***Flow rate-forcing* boundary:** Following the same steps as specifying *WSE-forcing* boundary, salinity values at freshwater inflow boundaries can be assigned together with flow specifications.

The Colorado River, the Lavaca River, and the Garcitas Creek are fresh water sources that flow into Matagorda Bay and flow measurements are available at three USGS gages. A zero salinity value is assigned at the *Flow rate-forcing* boundaries.

SIMULATION RESULTS: For the demonstration in Matagorda Bay, the CMS-Flow simulation was conducted for a 12-day period (29 November – 10 December 2005). Depth-averaged current and salinity fields in the system were retrieved from two snapshots of the CMS results, corresponding to the ebb and flood currents, respectively (Figure 9).

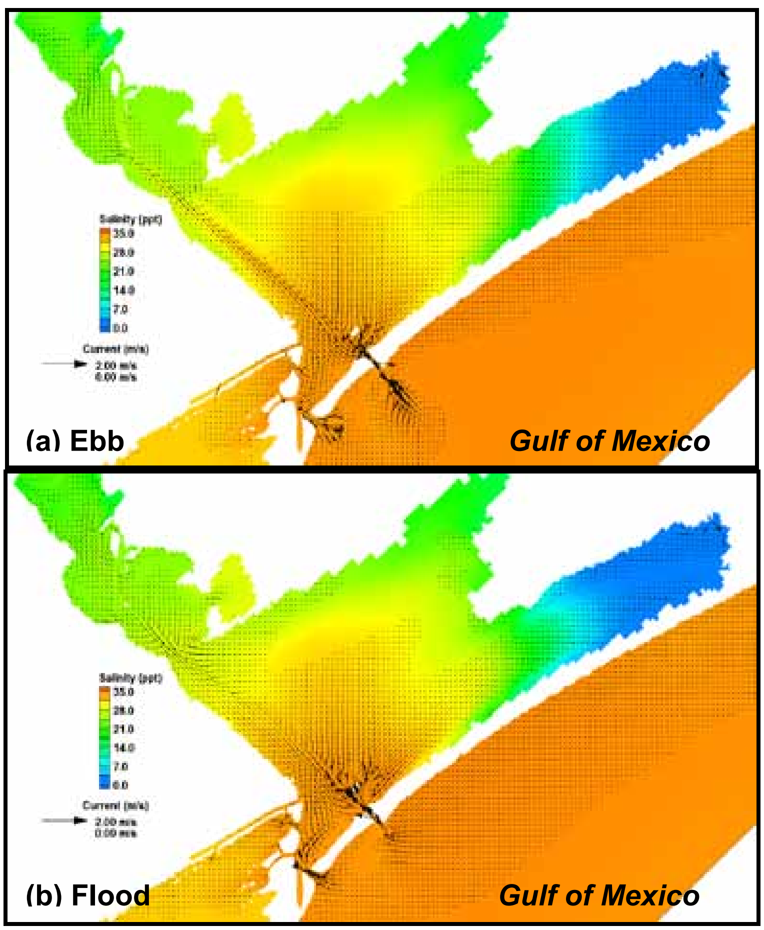


Figure 9. Salinity and current distributions during (a) the ebb current and (b) the flood current.

A relatively strong current exists along the MSC and the current speed is between 1.0 and 1.5 m/sec at the entrance of MSC during the ebb and flood tides. High salinity ocean water enters the bay through the entrance of MSC during the flood tide (> 32.0 ppt). Low salinity water hugs the coastline inside the bay and salinity is close to zero in the area adjacent to the mouth of the Colorado River. The large salinity gradient in the bay indicates the interaction between the freshwater plume and ocean water intrusion.

Model configuration and model performance were examined by comparing the measured and computed water surface elevations at BI. Salinity calculations in the system were validated by the data collected at sites MB, PP, BI, LB, and IP.

Water surface elevation comparisons are shown in Figure 10. The calculated tide at this location has good agreement with the measurements both in amplitude and phase. The correlation coefficient between the CMS and the data is 0.91 and the root mean square error (RMSE) is 0.06 m.

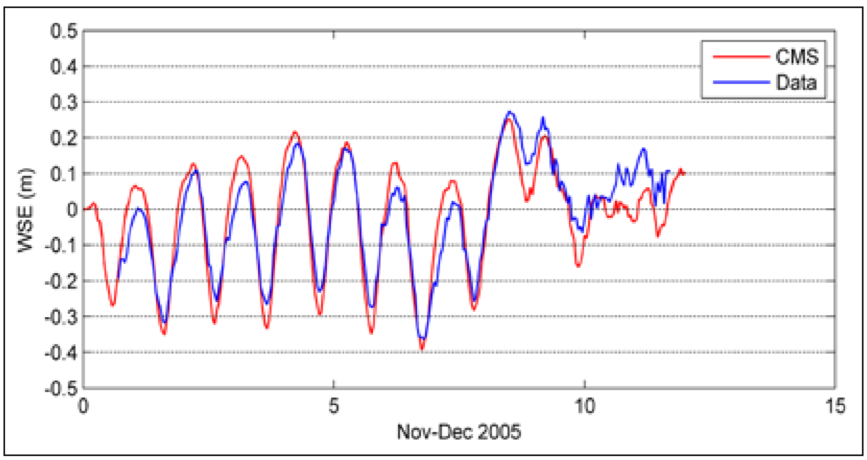


Figure 10. Calculated and measured water surface elevations at site BI for November-December 2005.

Figure 11 shows the salinity comparisons at sites MB, PP, BI, LB, and IP. Calculated salinity at the deeper sites (MB, BI, and IP) shows smaller temporal variations of less than 5 ppt and a larger variability of 5 to 8 ppt at the shallower sites (PP and LB) that are close to freshwater sources during this simulation period. A salt front in the bay clearly separates the high salinity water along MSC and the low salty water in the shallow area of the bay, indicating the interaction between freshwater inflows and ocean water intrusion.

Statistical parameters for the evaluation of the CMS performance are listed in Table 3. The correlation coefficients and RMSE indicate a better agreement between the CMS and the measurements at sites BI and PP, and poorer model and data correlations, and larger model deviation, at sites IP and LB. The sensitivity tests reveal that salinity transport in the bay is not only controlled by the interactions between tide and freshwater inflows, but is very sensitive to wind driven current as well. As pointed out by Kraus et al. (2006), the meteorological tide dominates the astronomical tide in Matagorda Bay and the salinity variations mostly respond to weather events or seasonal wind conditions.

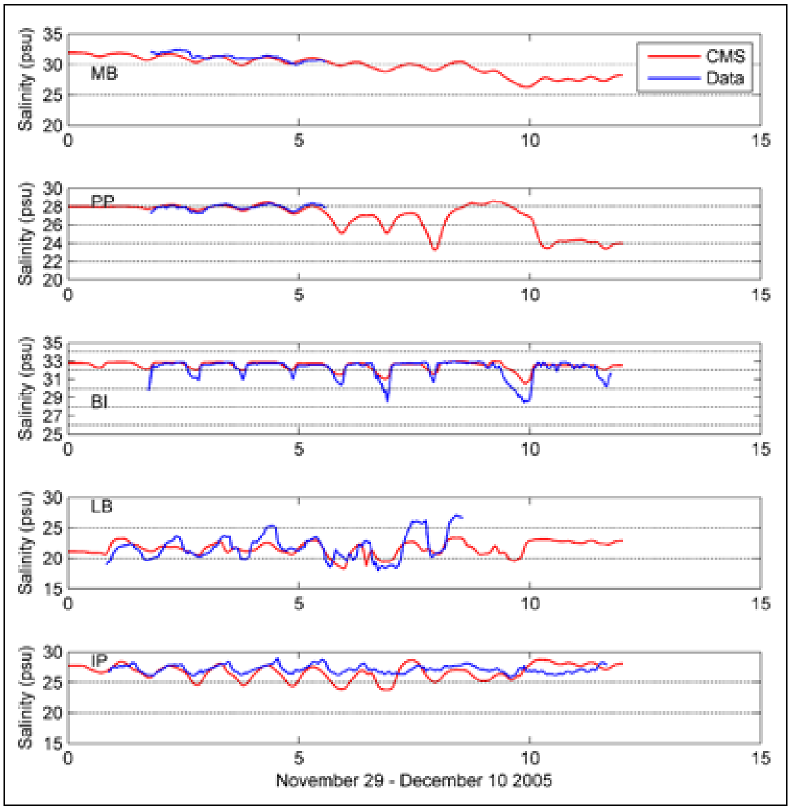


Figure 11. Calculated and measured salinity at sites MB, PP, BI, LB, and IP for November-December 2005.

Table 3. Correlation coefficients, root mean square errors (RMSE), and relative RMSEs (RRMSE) for computed and measured salinity.

Station	Correlation Coefficient	RMSE	RRMSE (%)
BI	0.888	0.666	13.3
MB	0.629	0.578	19.3
PP	0.698	0.221	14.7
IP	0.344	1.344	26.9
LB	0.598	1.626	18.1

The CMS simulations represent the salinity transport in Matagorda Bay to a level useful for comparison between engineering alternatives, and to understand general salinity patterns in the bay. Based on the study results, further improvement can be achieved through increasing knowledge of the temporal variation and spatial distribution of salinity and the interaction between tides, freshwater inflows and meteorological conditions in the bay.

CONCLUSIONS: The CMS' capability in conducting the depth-averaged salinity calculation in Matagorda Bay was demonstrated in this technical note. The example shows that the procedures to set up a CMS salinity calculation are straightforward and user-friendly. This estuarine

application provides the CMS validations, and well reproduces the temporal variations and spatial distributions of salinity in the example. Further improvement can be made as more data are collected in the future.

ADDITIONAL INFORMATION: This CHETN was prepared and funded under the Coastal Inlet Research Program (CIRP) and was written by Dr. Honghai Li (Honghai.Li@usace.army.mil, voice: 601-634-2840, fax: 601-634-3080) of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Dr. Christopher W. Reed (c.w.reedFL@gmail.com) of Reed & Reed, Inc., and Mitchell E. Brown (Mitchell.E.Brown@usace.army.mil) of ERDC, CHL. The CIRP Program Manager, Dr. Julie D. Rosati (Julie.D.Rosati@usace.army.mil), Dr. Zeki Demirbilek, Dr. Jeffrey P. Waters, and Dr. Lihwa Lin, the Coastal Engineering Branch, reviewed this CHETN. Files for the example may be obtained by contacting the author. This CHETN should be cited as follows:

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